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Correlation of the Failure Modulus to Fracture-Generated Surface Area in Uniaxially Compressed M43 Gun Propellant

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13. ABSTRACT *(Maximum 200 words)*

M43, a large-caliber, nitramine composite propellant, was tested in uniaxial compression at a rate of 100/s to 50.0% strain at temperatures from -40^0 to 60^0 C. Similar tests were performed to 20.0 and 10.0% strain. Failure modulus values (defined below) were measured and sufficient propellant was damaged so that closed bomb firings could be performed, which determined how the grain damage affected the pressure generation at ballistic pressures. After the burning rate was established using undamaged grains, the pressure-time curves from the damaged propellant were analyzed to extract the burning surface area profiles using the analysis program BRLCB. Results showed that the intercept of the linear fitted profile on the surface area axis, which was determined by plotting surface area against the amount of the propellant charge burned and fitting the initial 10% of that curve to a least squares fit straight line, seemed to be directly related to the logarithm of the failure modulus and the end strain. The resulting three curves, one for each level of strain, fell into a series that permitted the initial effective surface area to be predicted for any combination of failure modulus and the strain level within the fracture domain. These results seem to provide a method for assessing fracture damage by means of a simple mechanical measurement.

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1. INTRODUCTION

Attempts to link the relationship between mechanical response measurements and gun performance have made progress in the past 8 years.[1-12] Early work revealed that conventional mechanical parameters did not relate well to fracture susceptibility. The search for a simple mechanical parameter that could measure the propensity for a propellant to generate surface area upon mechanical failure resulted in the development of a failure parameter called the failure modulus,[3] E_f, that measures the rate at which the material strength is lost as a function of strain after material failure has begun. This parameter has been used as a guide in the development of new propellants to ensure that improvements in formulation and processing did not degrade the mechanical response characteristics of the material, which could result in poor performance and increased vulnerability response. It has also been successfully used to evaluate the relative fracture susceptibility among various propellant lots, or between unconditioned propellant and propellant that has been subjected to special conditioning that may affect its mechanical response, e.g., thermal cycling.

The failure modulus showed indications of direct usefulness when the changes of the vulnerability response related directly to changes measured in this parameter.[2] A correlation was found for propellant beds at low temperature subject to a shaped charge jet attack and led to other studies that attempted to make the correlation more direct. However, the relationship was made between *changes* in both responses, rather than directly relating the responses themselves. Most recently, a direct link between this failure parameter and a measure of the amount of fracture-generated surface area produced when M30 propellant was uniaxially compressed.[12] The failure modulus was measured and enough grains were damaged so that closed bomb firings could be performed to determine how the grain damage affected the pressure generation. A small (21 cc) closed bomb was used so that large numbers of grains did not have to be damaged to reach gun-like pressures in the closed vessel. After the burning rate was established using undamaged grains, the pressure-time curves from damaged propellant were analyzed for surface area, which produced a profile in the form of the surface area versus fraction of the charge burned. Analyzing these results showed that the intercept of the profile curve on the surface area axis, derived by fitting the initial 10% of the curve to a least squares fit straight line, was directly related to the logarithm of the failure modulus. The three resulting curves, one for each level of strain, fell into a series that permitted the effective surface area profile to be predicted for any combination of failure modulus and the strain level within the fracture domain. These results provided a method for assessing fracture damage for the M30 propellant by means of a simple mechanical measurement. In this study, the same procedure was applied to the nitramine composite propellant, M43.

2. EXPERIMENTAL PROCEDURE

2.1 Mechanical Response Measurement

The propellant response was measured using a specially designed servohydraulic tester,[4] illustrated in Figure 1. The machine allows for compression measurements to be performed at rates as great as 1000 s^{-1} for a specimen with a nominal length of 1 cm. Compression is arrested when contact occurs between the impact bell and cone. Therefore, the amount of specimen compression can be accurately predetermined by setting the anvil height. This contact between bell and cone not only stops the specimen compression, but it also shunts the force around the specimen. The nitrogen spring absorbs the mechanical energy and moderates the deceleration rate of the massive ram. The

force applied to the specimen is measured using the gauge inside the impact bell. During compressive response measurements, displacement is measured with a linear variable differential transformer in the actuator column and is corrected for machine stiffness.

The specimens were prepared from multiperforated M43 gun propellant grains whose formulation is listed in Table 1. The specimen preparation procedure began by cutting the sample with a diamond saw to a length of 1.00 cm. The ends were cut flat, parallel and perpendicular to the grain axis according to the specifications in an updated version of the test entitled "Uniaxial Compressive Gun Propellant Test".[13] Temperature conditioning was achieved by placing prepared grains inside the environmental chamber for a time at least twice that needed to reach thermal equilibrium (a total of 30 minutes). The specimen was then placed on the anvil and compressed. This testing took place within the conditioning chamber, so no transfer was required and, therefore, no thermal disruption occurred.

The final strain to which the specimen was taken is determined by the distance between the anvil and the force gauge when the bell and cone surfaces are mated. That distance was determined by placing a lead specimen on the anvil and performing a compression. This allowed for any dynamic affects to be taken into account that may have been overlooked in a static measurement. The percentage strain used in these tests was selected to be 50, 20, and 10%. From previous testing, it is known that failure of the grain occurs between 2 to 4% strain, depending upon strain rate and temperature.

The parameters measured in a response characterization test are the modulus (E), maximum stress (σ_m), strain at maximum stress (ε_m), stress at failure (σ_f), strain at failure (ε_f), and failure modulus (E_f). The definitions of these parameters are illustrated in Figure 2. The failure modulus is the slope of the stress-strain curve in the near-linear region between strain at maximum stress and twice that value. If no maximum stress occurs in the region of failure, the failure modulus is measured between the strain at

Table 1. Nominal Percent Composition of M43

Component	Percent Composition
Nitrocellulose (NC)	4
NC Nitration Level	12.6
RDX (Ground))	76
Cellulose Acetate Butyrate	12
Plasticizer	8

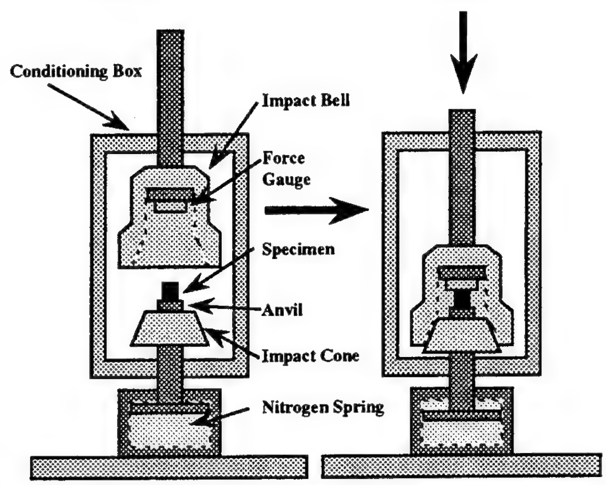


Figure 1. Servohydraulic Tester

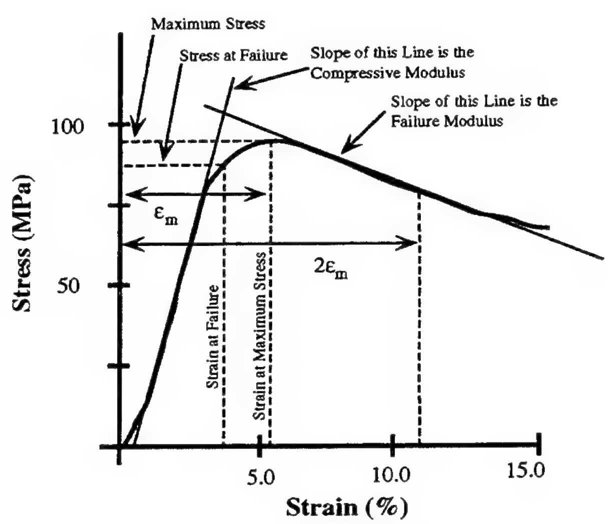


Figure 2. Mechanical Characterization Parameters

failure and three times that value. Measurement of the failure modulus was made at -40, -20, 0, 20, 40, and 60° C, and the reported values were determined from the average curve generated from five response curves, except in the -40° C case. At -40° C, the response of M43 was extremely brittle and failure occurred over a wide range of strain, which caused the average curve to be much less meaningful. At this temperature, therefore, the parameters listed were determined for the individual response curve and were then averaged. The specimen strain rate was chosen to be 100 s^{-1}, which is the order of strain rate encountered by the grains during a ballistic firing.

2.2 Fracture Generated Surface Area Measurement

The grains, damaged by uniaxial compression as outlined above, were burned in a mini-closed bomb (MCB) to determine the effect that the mechanical damage had on the pressure generation of the propellant. The MCB is a special, small-volume closed bomb.[5] The rate of pressurization during combustion is controlled by the intrinsic burning rate of the propellant and the surface area exposed to the flame. Since M43 is a low-vulnerability propellant and sometimes is difficult to ignite, 0.1 g of black powder was used as an ignition aid. After the propellant was burned and the resulting pressure-time curves acquired, the evolving surface area of the charge could be determined using the established burning rate of the propellant.

Undamaged specimens were burned in the MCB at the same loading density that was used in the damaged grain firings. These pressure-time traces were analyzed using the closed bomb reduction code BRLCB[14] to establish the burning rates for the M43 propellant for these tests. Once established, the surface area from all the pressure-time histories can be determined using the same code. The output from the code provides pressure in MPa and the corresponding surface area in square centimeters. This output was converted to intrinsic parameters of fraction burned and surface area ratio (S/S_0), by dividing the pressure by the maximum pressure and the surface area by the initial surface area of the undamaged grain (S_0), respectively. This allowed closed bomb runs with different charge masses, and corresponding pressure differences, etc., to be compared.

2.3 Details of the Experiment

Enough grains were damaged to provide two closed bomb firings for each temperature-strain condition. The initial series of tests done with M30 propellant[12] showed that two closed bomb firings could be performed with reasonable assurance of agreement. If the results from the two identically damaged propellant charges varied significantly, subsequent closed bomb tests were performed to resolve the differences. With six temperatures and three end strain conditions, a total of 45 closed bomb tests was conducted. This included some instances in which more that two firings were performed to verify the repeatability of the process.

3. RESULTS

The uniaxial compressive mechanical response of M43 propellant is shown in the stress versus strain curves presented in Figure 3. From these curves, the failure modulus is calculated as outlined above. Results of some mechanical property measurements are shown in Table 2. Figure 4 shows the natural log of the failure modulus plotted against temperature and indicates the nature of the response. These plots indicate that fracture *very rapidly* becomes more significant at lower temperatures. This is also reflected by the physical appearance of the grains after testing. Figure 5

shows typical 50% strain specimens after uniaxial compression. Figure 5c is included for comparison. It shows how M30 maintains greater integrity and shows the reduced level of fracture when damaged under the same conditions as M43 propellant. The failure modulus values reflect the increase in fracture observed in the tested specimens, but more importantly, the magnitude of E_f quantifies the extent of the fracture.

For each closed bomb firing, a surface area ratio versus fraction burned plot was obtained, as described above, which reflected the amount of surface area available to the flame throughout the propellant combustion. Figure 6 shows the theoretical and typical experimental values for the surface area ratio versus fraction burned for undamaged grains. Note that as the 19-perforated grains burn the surface area increases. This is due to the nature of the progressive grain design. This area profile is required to provide the gun with its designed performance. Any deviation from this profile reduces performance and in cases of severe deviation, can produce chamber pressure waves that can lead to catastrophic gun failure. The surface area profiles shown in Figure 7 are for grains damaged to 50% end strain at three temperatures. These deviations from the profile required for efficient gun firing are much more severe than those observed for M30 propellant[12] by about a factor of 3 and extend for much greater fraction burned. If the M43 surface area profiles observed here were present during a large caliber gun firing, large pressure variations would be present within the gun. The profiles for these damaged grains were analyzed using the procedure outlined below.

4. ANALYSIS

4.1 Method of Analysis

Many attempts were made in the previous study[12] with M30 propellant to associate the surface area curves obtained from the closed bomb results to the failure modulus: curve aver-

Table 2. Mechanical Response Parameters

T (° C)	Stress at Failure (MPa)	Strain at Failure (%)	Modulus (GPa)	Failure Modulus (GPa)
-40	122	2.75	5.97	-18.40
-20	140	3.40	5.28	-12.50
0	124	3.25	5.53	-1.58
21	92	3.01	4.30	-0.43
40	65	2.87	2.95	-0.27
60	52	2.56	2.59	-0.19

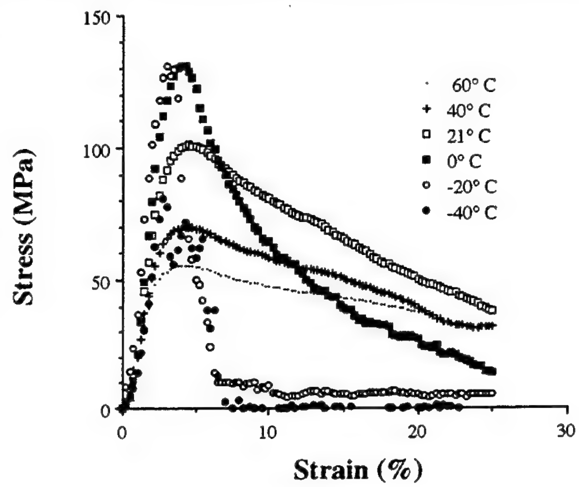


Figure 3. Stress versus Strain Curves for M43 from which Failure Modulus Values are Determined

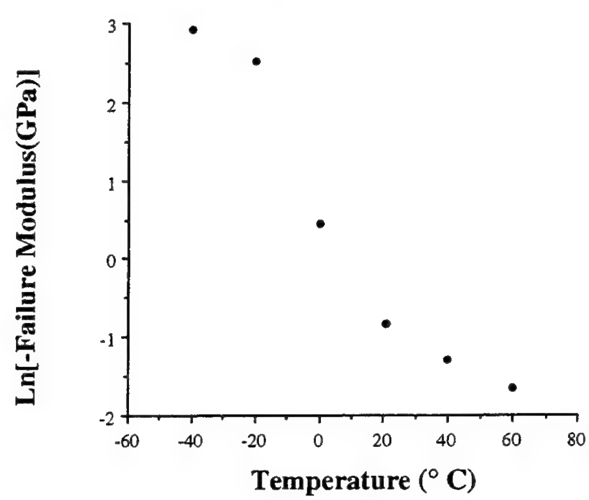
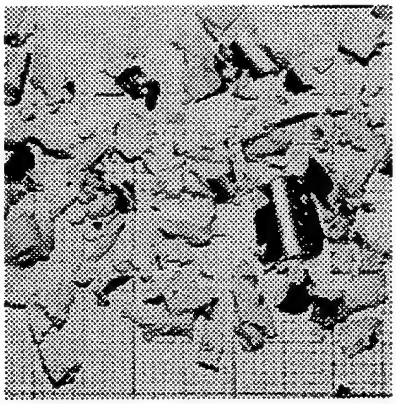
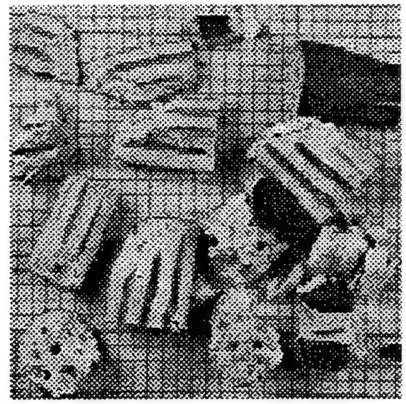


Figure 4. Ln of the Failure Modulus of M43 Propellant versus Temperature over the Temperature Range of Ballistic Interest

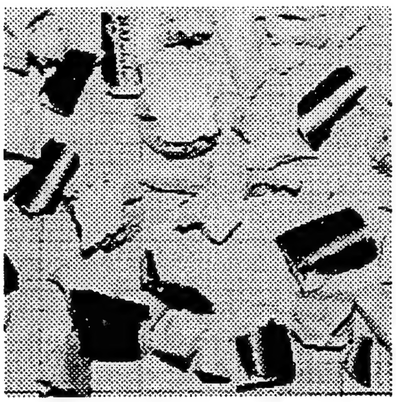


a. M43, -40°C

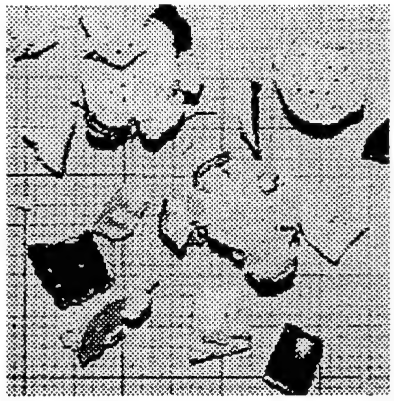
b. M43, -20° C



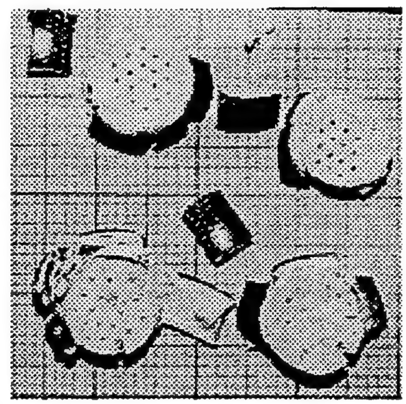
c. *M30*, - 20° C



d. M43, 0°C



e. M43, 21° C



f. M43, 40°C

Figure 5. Photographs of the M43 & M30 Propellant Specimens after Compression to 50% Strain

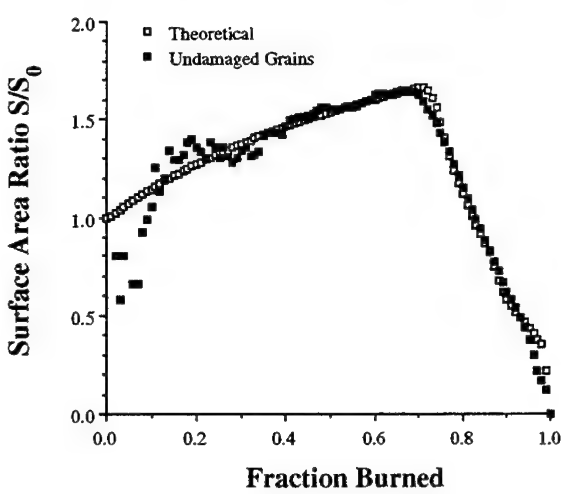


Figure 6. Theoretical and Undamaged Values of the Surface Area Ratio versus Fraction Burned for the 19-Perforation M43 Grains

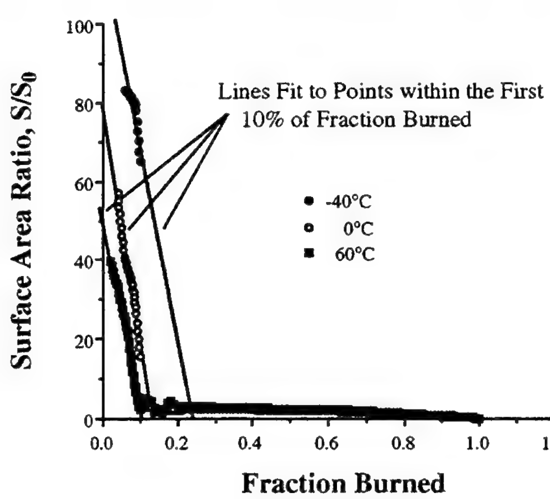


Figure 7. Surface Area Profiles for M43 Propellant Damaged at 50% Strain

aging, a comparison of areas under curves to a certain fraction burned, shifting of curves to match minimum surface area values, primary and secondary S/S_0 curve intercepts, and several other methods. The method that seemed to best characterize the deviation reflected in the curves and was still simple enough to be applied easily is described below.

The initial amount of surface area (S_i) available to the flame and the evolution of that surface area are both very important to the pressure generation rate during the early portion of the ballistic cycle. It would be desirable to incorporate into a set of numbers a measure of mass (pressure) generation deviation that can be expected due to fracture damage. To date, the method that best exhibits this information for the conditions thus far examined is to fit the points of the S/S_0 versus fraction burned curve, to 10% fraction burned, to a least squares fit. The intercept of this line (S_i/S_0) and its slope (M) characterize the important features mentioned above. The intercept indicates the initial surface area due to fracture, and the slope indicates the evolution of the area as the charge burns. (Three such lines are shown in Figure 7.) There are several reasons why this approach reflects critical aspects of mass generation within the gun. First, the conditions that result in significant deviations from planned mass generation within the gun are established very early in the ballistic cycle. Thus, it makes sense to use only the information contained in the early burning of the charge, i.e., the first 10%. If surface area variances begin to occur later in the cycle, the performance will be affected, but the chamber volume has increased significantly (and is continuing to rapidly expand), so that excess pressurization is more difficult to generate and pressure variations are likely to be less severe than those occurring at much smaller chamber volumes. Next, this method uses more than a few initial points to determine the value of the parameters being used to characterize the increased surface area. Those familiar with closed bomb analysis know that the most uncertain values generated in the process are those obtained at low fraction burned. This method of curve fitting eliminates the dependence of the value obtained from a few points in early, uncertain region, while still using values in this early combustion region to influence the parameter value. And lastly, by incorporating the points at higher fraction burned, i.e., to 10%, a measure of how the fracture generated surface area is evolving can be determined.

4.2 <u>Results of Analysis</u>

The above analysis procedure was applied to each of the closed bomb data sets. The intercept (S_i/S_0) of the linear least squares fit of S/S_0 versus fraction burned curve between the maximum value of S/S_0 and the value of S/S_0 at 10% fraction burned was obtained for the average curve for each end strain and temperature condition. To provide equal weight to each portion of the curve between the points being fit, values of S/S_0 were calculated at equal intervals of fraction burned, i.e., $\Delta FB = 0.002$, based on a linear interpolation between data points. This was necessary because high S/S_0 values cause more propellant to be consumed per unit time. Since data are recorded at equal time intervals, the representation of the data by intervals of fraction burned resulted in larger intervals between data points for higher values of S/S_0. Since greater levels of propellant damage result in higher initial values of S/S_0, for severely fractured grains, there was a significantly lower density of data points at higher values of S/S_0. This lower point density can skew the fitted curve by affecting the intercept and slope, as can be seen in Figure 8. The linear interpolation procedure described above was employed to make the derived parameters more sensitive to fracture damage. The average values derived from this procedure appear in Table 3 along with the corresponding values of the failure modulus.

Table 3. Average Values of Failure and Surface Area Ratio Parameters

Temperature (° C)	E_f (GPa)	Ln $(-E_f)$	*Average Intercept* (S_i/S_0) 50%	20%	10%	*Average Slope (M)* 50%	20%	10%
60.0	-0.19	-1.655	52.9	9.74	-	-500	-102	-
40.0	-0.27	-1.295	58.9	7.92	-	-352	-68.6	-
20.0	-0.43	-0.837	60.9	23.4	-	-220	-249	-
0.0	-1.58	0.457	78.1	43.7	19.8	-591	-401	-231
-20.0	-12.50	2.526	92.4	46.3	27.5	-450	-560	-305
-40.0	-18.40	2.912	106.5	61.6	24.5	-351	-509	-296

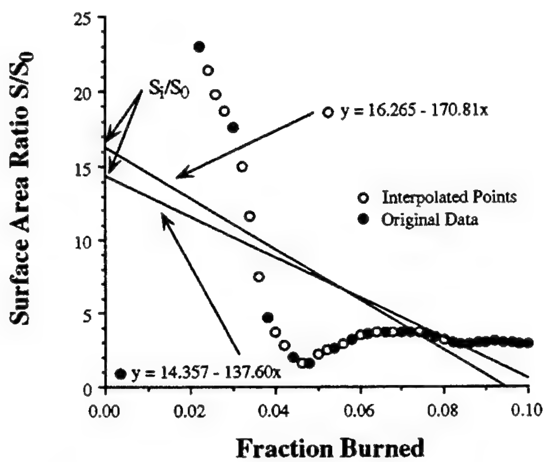
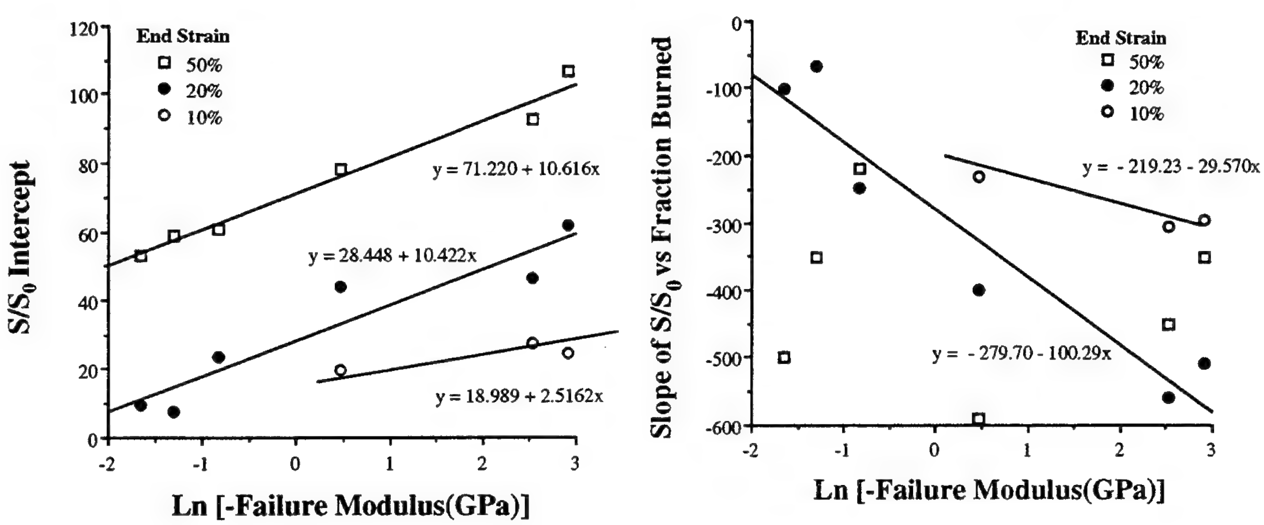


Figure 8. Original and Interpolated S/S_0 versus Fraction Burned Curves with Corresponding Characterization Parameters

If these intercept values are plotted against the logarithm of the failure modulus for each of the end strain levels and a linear least squares fit is made to the points, the plots in Figure 9 result. Plots similar to those in Figure 9 were generated for M30 propellant,[12] and resulted in linear relationships being demonstrated between both the intercepts and slope values of the lines and the end strain values of each line. This permitted characterization of the initial surface area and its evolution over the first 10% of fraction burned in terms of the end strain, the failure modulus, and the fraction burned. This same relationship is only partially realized for M43 propellant. If the fitting parameters from the straight lines in Fig-



a. Average Surface Area Ratio Intercept

b. Coefficient of Fraction Burned (Slope)

Figure 9. Average Least Squares Fit Parameter versus Ln of the Failure Modulus for S/S_0 versus Fraction Burned at Each End Strain

ure 9a are plotted against end strain, the fitting *constants* show a linear dependence with end strain, as shown in Figure 10a. However, a plot of the fitting *slopes* of the lines in Figure 9a versus end strain show that the relation does not appear linear but seems to be more plateau-like. The curve runs from 2.52 at 10% end strain to a value of 10.5 somewhere between 10 and 20% end strain and then remains at that level. This implies that at higher end strain levels (somewhere between 10 and 20%) the rate of initial surface area increase with $\ln(-E_f)$ becomes constant. This is consistent with the mechanical response curves, shown in Figure 3, which show that for curves with a lower failure modulus value (below -1.00), the material has no strength above 20% strain. This implies that almost all the damage done to the propellant under those conditions occurred before 20% strain and that very little additional damage is done afterward. If the equations in Figure 10 are substituted into the relationships shown in Figure 9a, the S/S_0 versus fraction burned curve intercept can be represented in the general form $y = [intercept] + [slope] \ln(E_f)$

for $10\% \leq \varepsilon \leq 20\%$, by

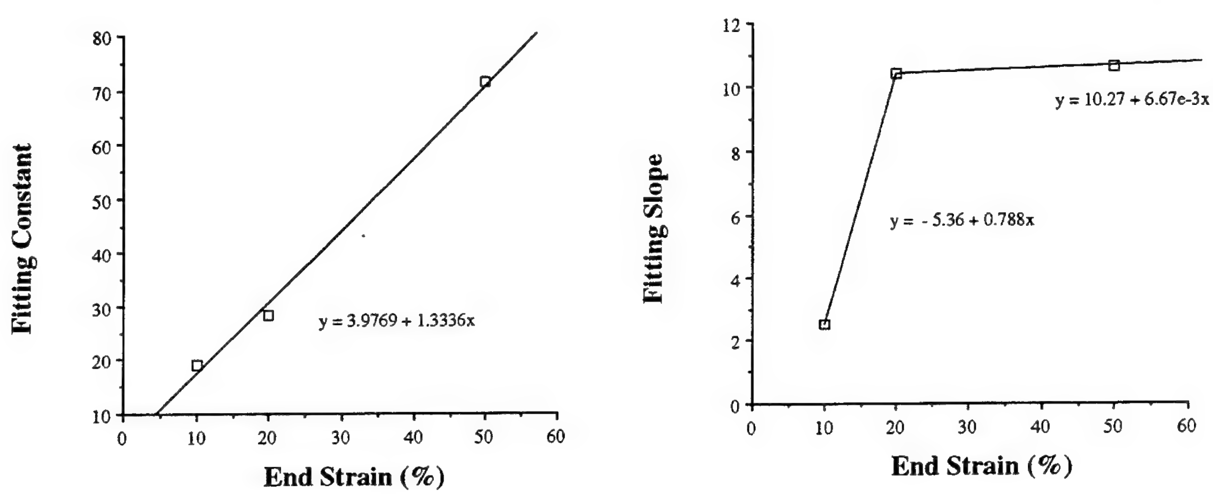
$$S_i/S_0\,(\varepsilon, E_f) = [3.9769 + 1.3336\,\varepsilon] + [-5.36 + 0.788\,\varepsilon] \ln(-E_f)\,; \qquad (1)$$

and for $\varepsilon > 20\%$, by

$$S_i/S_0\,(\varepsilon, E_f) = [3.9769 + 1.3336\,\varepsilon] + [10.27 + 0.007\varepsilon] \ln(-E_f). \qquad (2)$$

These relationships can be used to predict values of effective initial fracture-generated surface area, given the measured failure modulus, and the end strain. Figure 11 shows a plot of these equations.

As mentioned above, a similar result was obtained for the slope of the line that is fit to the average S/S_0 versus fraction burned curves for M30. The values of average slope for M43 appear in Table 3 and are plotted against $\ln(-E_f)$ in Figure 9b. Again, the 10% and 20% data are compatible with a linear dependence with $\ln(-E_f)$. Least squares best fits can be performed on these points to characterize the evolution of the surface area as a function of fraction burned, but only to about 20% end strain. As can be seen for the 50% end strain, the points are very scattered and no linear correlation with $\ln(-E_f)$



a. S_i/S_0 Curve Constant

b. S_i/S_0 Curve Slope

Figure 10. S_i/S_0 Intercept Parameters from Figure 9a versus End Strain

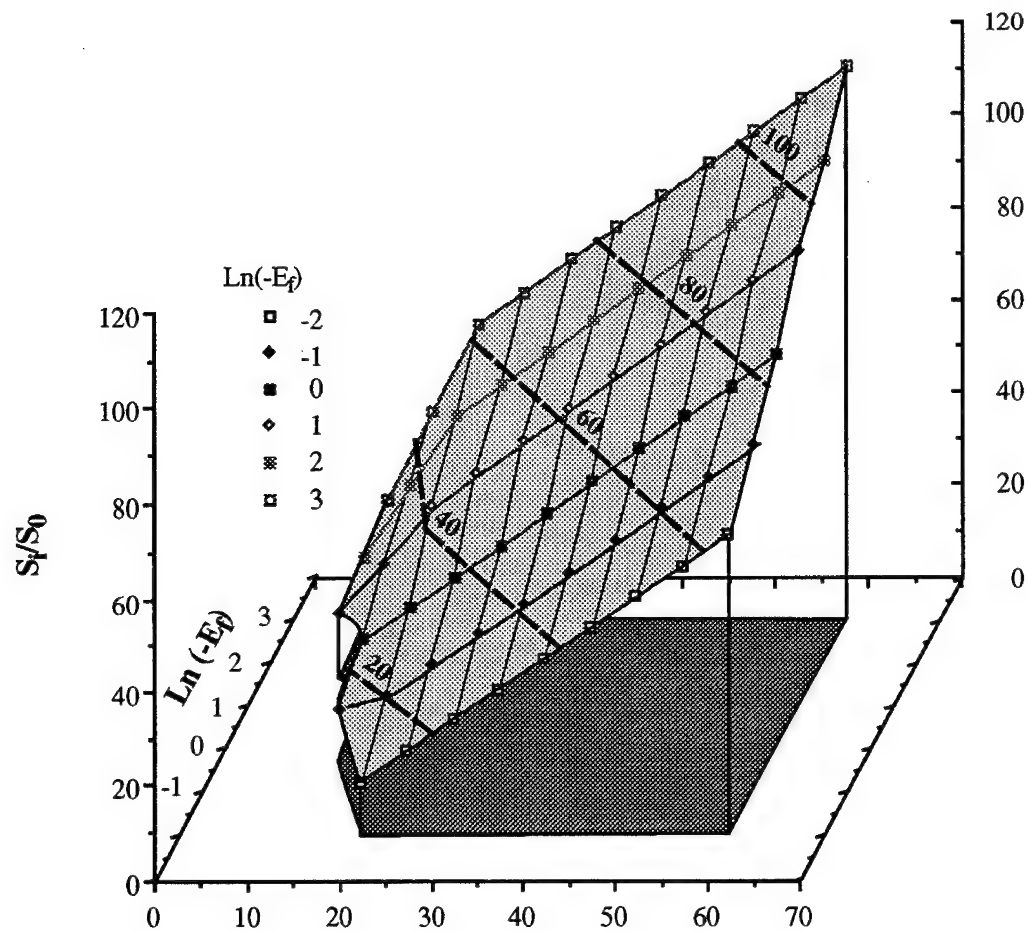


Figure 11. The S_i/S_0 Surface from Equations 1 & 2

exists. In the case of M30, the evolution of the curve was characterized by increasing initial surface area with lower values of E_f and higher strains. As the charge burned, the further the initial value was from the original programed value, the more rapidly the surface area attempted to return to the programmed surface area value. This result implies that there was still *some* memory in the damaged structure of the programmed value of the grain. For M43, somewhere above 20% strain it seems as if the evolution of surface area has lost most of its dependence on the initial structure of the propellant grain. This situation results in unstable evolution of S/S_0 and can lead to erratic mass generation processes similar to conventional bulk-loaded liquid propellant combustion, where the evolution of effective surface area can sometimes be very erratic. However, when the same operation is performed on the constants and coefficients of the equations of the lines found in Figure 9b, for 20% end strain and lower, the coefficient of the effective surface area curve can be approximated, as above, by placing the appropriate end strain and failure modulus values in the following equation:

for $10\% \leq \varepsilon \leq 20\%$,

$$\text{Slope}(\varepsilon, E_f) = [-159 - 6.05\,\varepsilon] + [41.2 - 7.07\,\varepsilon]\ln(-E_f)\,; \tag{3}$$

for $\varepsilon > 20\%$ end strain, the evolution of the surface area profile seems to be erratic.

These equations can be combined to produce the effective surface area profile versus fraction burned (usually designated as Z) for the first 10% of the fraction burned for some of the conditions studied here.

For an end strain between 10 and 20%,

$$\begin{aligned} S/S_0\,(\varepsilon, E_f, Z) &= S_i/S_0\,(\varepsilon, E_f) + \text{Slope}\,(\varepsilon, E_f)\,Z \\ &= [3.9769 + 1.3336\,\varepsilon + (-5.36 + 0.788\,\varepsilon)\ln(-E_f)] + [-159 - 6.05\,\varepsilon \\ &\quad + (41.2 - 7.07\,\varepsilon)\ln(-E_f)]\,Z. \end{aligned} \tag{4}$$

For end strains greater than 20%, the initial surface area ratio can be given by

$$S_i/S_0\,(\varepsilon, E_f) = [3.9769 + 1.3336\,\varepsilon] + [10.27 + 0.007\varepsilon]\ln(-E_f), \tag{5}$$

with the surface area evolution somewhat erratic.

The domain over which these relationships can be expected to apply is somewhat unclear. Since it is unknown exactly at what end strain the plateau edge begins in Figure 10b and at exactly what end strain above 20% the evolution of surface area becomes erratic (Figure 9b), the equations presented have made assumptions that the end strain for both of these boundaries is about 20%. In any case, the value of strain must be above 10% to use these equations.

5. DISCUSSION

The above equations can be used for several purposes. As stated, if the stress state of the propellant grain is known and the failure modulus has been measured, then the effect of the initial surface area can be evaluated. The effects of the augmented surface area on combustion for the first 10% of fraction burned can be evaluated by using Equation 4 to predict an effective surface area profile during the early combustion as long as the end strain conditions are not violated. The prediction may not, however, show the dynamic effects of the surface area evolution that could affect the generation and propagation of pressure waves within the gun chamber, e.g., the enhancement of combustibility resulting from freshly fractured surfaces, but it should, nonetheless, provide a more accurate assessment of the dynamic pressures.

These equations could also be used to predict conditions in which fracture-generated surface may become a significant problem. The time-temperature equivalence of M43 and other propellants has been established[9] over the temperature range of ballistic interest and has been related to the strain rate for more than four orders of magnitude.[10] Using this information, the strain state of a propellant can be predicted for a certain strain rate deformation, at a particular temperature. In the referenced studies, it was shown that the time-temperature equivalency could be extended to predict the failure modulus, as well. This allows for an estimation of the degree of damage and its effect on combustion for a wide variety of conditions, even those outside the area of available physical measurement. If ballistic codes are used to show when certain surface area profiles subject a system to unacceptable performance, these equations can be used with the appropriate mechanical response parameters to predict when and where these conditions are likely to arise.

Other uses will become evident as the application or problem becomes more well defined. For a long time, the modeling community has had to rely on relatively arbitrary surface area augmentation algorithms. Now, for both M30 and M43, a method is available that relates a relatively easily determined mechanical parameter to a surface area profile during the early phase of combustion.

6. CONCLUSIONS

A correlation has been established that relates the end strain state of uniaxially compressed M43 gun propellant grains to a surface area profile that characterizes fracture-generated surface area during early combustion. This correlation is based on an easily measured mechanical parameter called the failure modulus. This parameter, shown in an earlier study to predict fracture surface area profiles for damaged M30 propellant,[12] has been shown to predict the initial surface area ratio for grains tested to 50% strain over a temperature range of -40° C to 60° C. In addition, the evolution of that surface area has been characterized for grains undergoing compression to levels as high as 20%. Between 20 and 50% compression, the evolution of the fracture surface area was measured to be erratic. This may be the result of the extremely brittle nature of the response that produces very large S/S_0 values and causes the loss of load-bearing ability of the material. The damage being done to the grain is thereby done at an unknown strain level.

The effective surface area profile during early combustion has been related to the logarithm of the failure modulus for each of the end strain conditions tested, and the parameters determined in these linear correlations (the constant and coefficient of each relationship) have been shown to be linear functions of the strain. The result of this is a method by which an equivalent surface area profile can be generated, based on the level of strain and the established failure modulus, that has wide application in the modeling and propellant development communities.

7. FUTURE STUDIES

This is the second propellant type to undergo this series of tests. Tests are currently under way to characterize single (M14) and double (JA2) base propellants. Initial results from these studies indicate that the level of fracture surface area generated in both of these propellant types is significantly lower than for M30 tested under similar conditions, which would make them very much less fracture susceptible than M43. While these results were qualitatively known, the assignment of specific surface area values as a function of simply measured parameters is a great aid in predicting changes in performance due to fracture generation. Also, in this current study, to clarify the domain over which the stated equations are valid, additional tests at selected end strain levels will be required. This added information, along with the time-temperature equivalency established for each of these groups, should provide a valuable tool to predict the augmentation of pressure generation attributable to fracture damage in ballistic systems.

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